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Experimental study of the effect of arc root fluctuations on the injection in Suspension Plasma Spraying

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Abstract: Suspension Plasma Spraying (SPS) allows depositing finely structured coatings. This paper presents an analysis of the influence of plasma instabilities which control the interaction plasma jet-zirconia suspension. A particular attention is paid to the treatment of suspension jet or drops according to the importance of voltage fluctuations (linked to those of arc root) and depending on the different spray parameters such as the plasma forming gas mixture and the suspension momentum. By observing the suspension drops injection with a fast shutter camera and a laser flash triggered by a defined transient voltage level of the plasma torch, the influence of plasma fluctuation on drops fragmentation is studied through the deviation and dispersion trajectories of droplets within the plasma jet.

Keywords: Suspension Plasma Spraying, Arc root fluctuations, coatings

1. Introduction

Suspension plasma spraying (SPS), allows forming finely structured coatings. With this process, submicron particles, using a liquid feedstock carrier, can be sprayed onto a prepared substrate [1,2,3]. When the suspension is injected into a Direct Current (D.C.) plasma jet at atmospheric pressure, first the liquid is fragmented into dispersed droplets a few microns in diameter, second the droplets of solvent are vaporized and transformed into plasma [4,5], and finally the solid particles of the suspension contained within droplets are melted and accelerated onto the substrate where they flatten to form splats [6]. Due to the finer powder injected compared to conventional, the coating thickness can vary between a few tens microns and a few hundreds of micron depending on spray conditions.

However, the arc fluctuations of the torch, which results in a transient behavior of temperature and velocity fields of the plasma jet, are expected to have a strong influence on the suspension penetration, and particles trajectories. Hence, materials (liquid or solid) embedded in the plasma flow undergo strong variations of the thermal and kinetic transfers.

The aim of this study is to determine which spray parameters have to be controlled to get thermal and kinetic effects on the particles which are as less as possible time dependent in order to better monitor their flattening onto the substrate. Understanding the transient interaction between suspension jet and fluctuating plasma jet, should permit to ensure the repeatability of coating properties (microstructural, electrical, and thermal). Hence, the injection of the suspension is observed with a fast shutter camera coupled to a laser flash and triggered by a defined instantaneous voltage level of the plasma torch. Pictures taken with this device, allow observing the time resolved suspension-plasma interaction for different torch working parameters.

First will be presented the experimental facilities, then the plasma suspension interaction study and at last the optimization of injection parameters.

2. Experimental Facilities

2.1 Injection System of the Suspension

The injector system is composed of tanks in which the suspension is stored, and a stainless steel tube with its extremity a diaphragm on which a calibrated hole is machined. The injector axis, crosses the torch axis close to the nozzle exit, the angle between both directions being 80 °. The injection velocity is adjusted by monitoring the tank pressure using compressed air. This system permits to work with drop injection velocities between 23 m/s and 35.5 m/s. The Suspension of yttria stabilized zirconia (YSZ) is made with a powder mass percentage of 7% dispersed within a solvent (ethanol). The suspension jet shows weak instabilities within the first centimeters following the injector hole and is completely fragmented into drops after travelling a distance of 30 +/- 2 mm. The jet before fragmentation is approximately 200 µm in diameter and the drops show a mean diameter of 290 µm. Therefore, it is possible to inject the suspension, either as a continuous jet or as drops, depending on the distance between the injector tip and the torch axis. The liquid is characterized by means of an optical system which is described further down. With a pressure tank of 4 10^5 Pa, the drop velocity is 27 m/s, the mean distance between two consecutive drops is about 730 µm, the number of drops emitted per unit time being 3.7 10^4 s^{-1}. In this condition the liquid flow rate is of 0.47 $cm^3.s^{-1}$.

2.2 Plasma Torch and Optical System

A commercial D.C. plasma torch (PTF4 from Sultzer Metco) is used with an anode nozzle diameter of 6 mm. The working parameters of the torch (arc current intensity, voltage, thermal efficiency, gas mass flow rate) are measured and recorded for each experiment, using a home made computer code.

The plasma is generated with Ar/H_2 (45/15 slm). The Ar/H_2 plasma is generated with an arc current of 500 A, the voltage shows a mean value $\overline{V}$ =60 V, and fluctuations of +/-30 V,peak to peak. These arc instabilities, involve a high plasma jet fluctuation in length and position.

The set up to observe the suspension penetration within fluctuating plasma jets consists of a fast shutter camera coupled with a laser flash at 808 nm. The originality of this system is that the image acquisition is triggered when the arc voltage reaches a given threshold. Therefore, the treatment of the materials can be observed and correlated to an instantaneous state of the plasma flow. Figure. 1 represents the time resolved triggering of the system used.

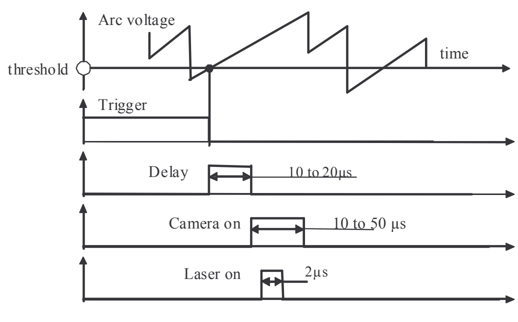

Figure 1: Timing: Synchronization of the observational system.

The voltage fluctuations are recorded by numerical oscilloscope. When the arc voltage reaches the chosen threshold, voltage pulse activates the aperture of the shutter camera after time delay corresponding to the time of flight of the plasma between the nozzle and the optical axis of the camera. During the aperture of the shutter (10 µs), a laser shot is sent to illuminate the suspension jet, which otherwise is not sufficiently luminous compared to the plasma flame.

3. Interaction Plasma/Suspension

The penetration of the suspension is studied for the Ar/H2 (45/15 slm) plasma gas, an arc current 503 A, a mean arc voltage of 60.6 V, torch thermal efficiency 59%, and a specific enthalpy 13.3 MJ/kg. The Fig. 2 presents the typical waveform of the arc voltage, with a period approximately equal to 200 µs.

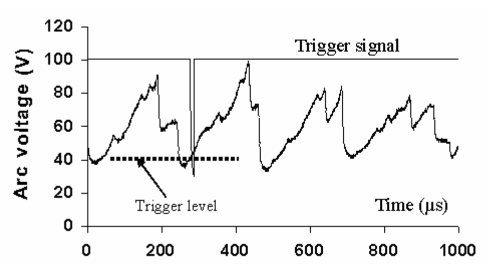

Figure 2: Typical voltage waveform of an Ar/H2 (45/15 slm) plasma gas. (nozzle internal diameter 6mm, I=503 A).

The voltage fluctuation shape, besides the plasma forming gas composition, is linked to the geometry of the anode nozzle and the cathode together with the gas compressibility effects. Moreover, on this wrapping of 200 µs, “restrike oscillations” of the arc root at higher frequencies can be identified. Therefore, the instantaneous electrical power supplied to the plasma gas is fluctuating in a frequency range of 2 to 10 kHz. The breakup mechanisms of the suspension drops, according to the constant variation of the arc voltage, are observed thanks to the detection system triggered by a defined voltage level of the plasma torch. Figure. 3 represents the fragmentation of the suspension for two different instantaneous plasma states.

The scale is given by the two horizontal dashed lines which are separated by the distance corresponding to the nozzle internal diameter (6 mm). Figure. 3a shows the picture taken for an instantaneous arc voltage of 65 V.

The distance between the injector tip and the torch axis is 20 mm, at that distance the jet is not yet fragmented but shows weak instabilities which wavelength is about 900 µm.

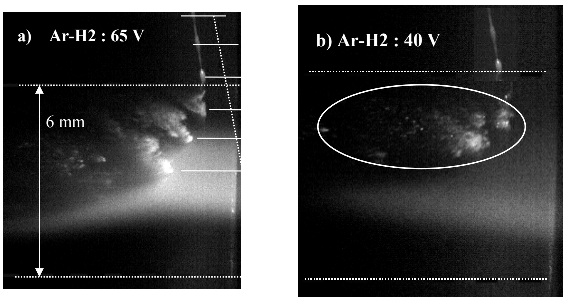

Figure 3: Interaction plasma-suspension according to triggering level. Pictures according to triggering of Fig. 2 injection velocity of 26.6 m/s, and distance between the injector tip and torch axis 20 mm. a) triggering level of 65 V, b) triggering level of 40 V.

When the suspension jet penetrates the plasma, it is broken at the neck of the instabilities by the shear stress. Hence, several individual clouds of materials (liquid and/or solid) within the plasma jet can be clearly identified. These clouds are composed of a compact head of suspension and behind it, some sort of tail with tiny droplets and/or solid particles. The different clouds are equally spaced into the plasma, this distance is represented in the Fig. 3a by the horizontal white lines. The distance between two successive clouds corresponds to the wavelength of the jet instabilities before entering the plasma. This means that the initial velocity of the suspension (26.6 m/s) is kept along the injection axis after its penetration within the jet. To understand the time interaction plasma-suspension, it is important to evaluate the time needed by a drop to reach the plasma axis. This time required by the drop to travel from the upper edge of the plasma down to its axis (3 mm), is of 100 µs. It corresponds to an half period of the plasma mean fluctuation which is 200 µs. Therefore the cloud which travels towards the plasma jet axis is treated by one puff of plasma, and the treatment of materials is strongly dependent on the properties of this puff (e.g. ,velocity and specific enthalpy).
The picture of the Fig. 3b shows the interaction plasma-suspension with a low triggering level, 40 V. When this picture is taken the plasma is characterized by low velocity and mass enthalpy. In this half period the shear stress “$\rho_p u^2$”applied to the suspension is lower than that of the preceding half period. But, in this picture no drops can be observed at the plasma jet axis position. This is due to the fact that the drops which are absent have penetrated into the plasma 100 µs before this picture, was taken, i.e. during the preceding half period. This preceding period is characterized by higher mass enthalpy, temperature and velocity. Thus, these clouds, which are absent, have been swept downstream by the preceding puff of plasma.

According to the high arc voltage fluctuations, each particle contained within the fragmented drops, has its own thermal and kinetic histories which depends on the moment when it enters into the plasma.

4. Influence on coating growth

The fragmentation mechanism described above suggests that primary drops are progressively fragmented to form the tail, composed of tiny secondary droplets, and the head, which contains the major part of solid particles. The tiny droplets, consisted of particles, travel in the plasma jet fringes and give rise to fine particles which probably will not undergo an efficient plasma treatment. The solvent, present in heads, is expected to rapidly vaporize and heads can form a sort of agglomerate. If the latter conserves its integrity during its travel in the plasma jet, it can be expected that the coating growth depends on the distribution of these agglomerates within the coatings. A cross section observation by scanning electron microscopy (SEM) does not necessarily enable one to highlight the presence of such agglomerates because of an effect of averaging of multiple passes. However, since the plasma jet is “naturally pulsed” because of arc root fluctuations (100 µs halp period) and the substrate is displaced at 0.8 $m.s^{-1}$ during deposition, it can be expected that these agglomerates are distributed on the coatings surface with a step of the order of 80 µm.
Figure 4 presented a SEM surface of an Yttia (8mol%) Stabilized Zirconia (YSZ) coating produced using a suspension with 20 % mass load. It can be observed the presence of sort of agglomerates uniformly distributed all over the coating surface. When measuring the mean distance between these agglomerates, it is found about 25 µm what is close to the order of magnitude deduced from the arc root fluctuations (80 µm).
Figure 5 shows a detailed view of previously mentioned agglomerate. It can be observed it is composed of tiny solid particles (about 100 nm in diameter) trapped in melted materials. These observations lead to suggest that coating growth is mainly due to the stacking of such agglomerates what implies that the coating is, these experimental conditions, composed of melted and also partially melted materials.

5. Conclusion

A time resolved observation of the interaction between the plasma jet and the suspension which are both involved in the Suspension Plasma Spraying process has been carry out. The optical system is triggered when a previously defined voltage is reached, so that the instantaneous energy level of the plasma, and related properties of the flow, can be correlated to the liquid drop treatment. The time required by a drop, or a part of liquid, to cross over the jet was found to be of prime importance, particularly when it is close to the period of the arc fluctuations. An important disparity of material treatment was observed in that case, depending on the time at which the liquid penetrated the jet, corresponding to either a high or a low instantaneous power level. The volume, in which the solid material is imbedded after fragmentation, seemed to be elongated or contracted at the rhythm of arc fluctuations, so that, in combination with the substrate movement during spraying, a pseudo-periodic structure was observed on some coatings.

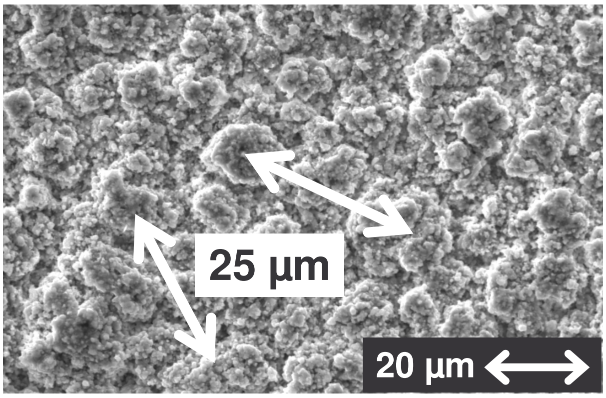

Figure 4: SEM surface coating (YSZ)

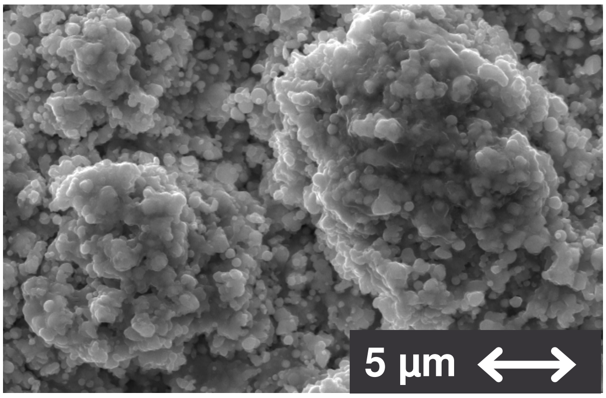

Figure 5: SEM surface coating (YSZ)-Detailed view of a surface agglomerate

6. Acknowledgements

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